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Vorgeschlagene Zitierweise/Suggested citation:
Molines, Jorge; Medina, Josep R. (2019): Crown Wall Stability of Cube and Cubipod Armored Mound Breakwaters. In: Goseberg, Nils; Schlurmann, Torsten (Hg.): Coastal Structures 2019. Karlsruhe: Bundesanstalt für Wasserbau. S. 3-9.
https://doi.org/10.18451/978-3-939230-64-9_001.

Coastal Structures 2019 - Nils Goseberg, Torsten Schlurmann (eds) - © 2019 Bundesanstalt für Wasserbau
ISBN 978-3-939230-64-9 (Online) - DOI: 10.18451/978-3-939230-64-9_001

Crown Wall Stability of Cube and Cubipod Armored Mound Breakwaters

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Abstract: Mound breakwaters usually have a concrete crown wall to reduce the amount of quarry material and to improve accessibility. Popular methods to design crown walls consider the same value of the horizontal pressure in the lower edge of the vertical wall and the seaward edge of the crown wall base. Up-lift forces are calculated assuming a triangular pressure distribution with a value given by pressures in the vertical wall. This assumption is reasonable in structures where the foundation level is below the sea water level, but may significantly differ from reality in crown walls with foundation levels above the sea water level. This study focuses on the influence of the foundation level on the crown wall stability analyzing 2D physical tests of cube and Cubipod armored breakwaters with crown wall.

Keywords: Crown wall, Cubipod armor, cube armor, mound breakwater, wave forces

1 Introduction

Mound breakwaters usually have a crown wall to increase the crown freeboard (R_c) in order to decrease wave overtopping and consumption of quarry materials (Figure 1). Moreover, crown walls improve accessibility and provide space to install a variety of facilities for port services. Crown walls usually have the foundation level above the sea water level in order to be constructed using ground equipment. Crown walls must resist wave forces and earth pressure due to armor layers and filters. Bruun (1985) described four types of failure modes of a crown wall: (1) sliding, (2) overturning, (3) cracking and (4) foundation failure; sliding is the most common failure mode.

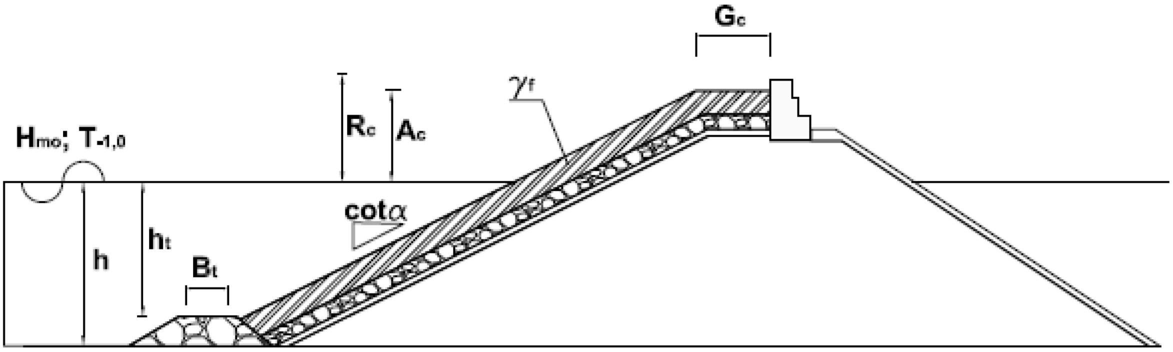

Fig. 1. Cross-section of conventional mound breakwater with crown wall.

Existing methods to calculate wave forces on crown walls can be classified in two groups:

1. Methods based on pressure distributions: These methods evaluate the horizontal and up-lift pressures acting on the crown wall (Figure 2a). These methods evaluate: (1) the horizontal

force associated to an exceedance probability, (2) the horizontal pressure in the lower edge of the vertical wall associated to an exceedance probability and (3) the vertical pressure that acts in the seaward corner of the crown wall base assuming pressure continuity between horizontal and up-lift pressures. The horizontal force and horizontal pressure associated to an exceedance probability may not occur at the same time and therefore the pressure continuity may not occur.

2. Methods based on horizontal and vertical forces: These methods evaluate the horizontal and up-lift forces without describing the pressure distributions (Figure 2b). In these methods, the forces are calculated assuming rectangular or trapezial distributions around the pressure sensors used in the laboratory. Those methods calculate the horizontal force (Fh) and the maximum up-lift force (Fv(Fh)) generated by the same wave (although both events can be slightly separated in time).

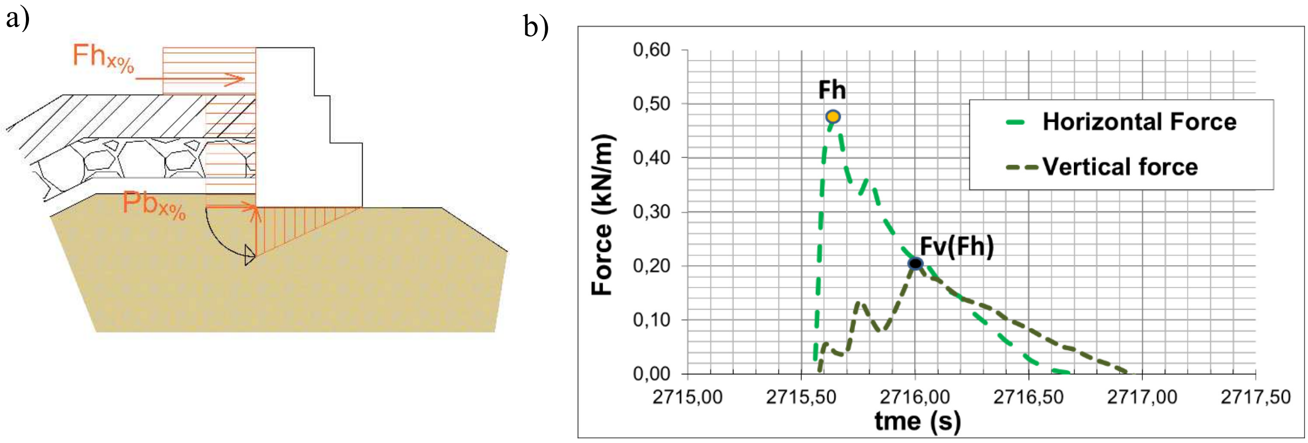

Fig. 2. Forces estimated with methods that provide a) pressure distribution and b) wave forces on crown wall.

Pedersen (1996) proposed a method to evaluate the pressure distribution on a crown wall based on 2D physical tests with irregular waves in non-breaking conditions, assuming pressure continuity between the vertical wall and the crown wall base with three types of armor layers (rocks, cubes and Dolos). Pedersen (1996) proposed a method to evaluate the forces and pressures associated to an exceedance probability of 0.1% ($Fh_{0.1\%}$ and $Pb_{0.1\%}$) with no influence of the type of armor unit. Norgaard et al. (2013) extended the method of Pedersen (1996) to evaluate wave forces on crown walls of rock armored mound breakwaters in breaking conditions.

Martín et al. (1999) conducted 2D physical tests of the Gijón breakwater with regular waves in non-breaking conditions. Martín et al. (1999) assumed pressure continuity between the vertical wall and the crown wall base and included the influence of the type of armor through fitted coefficients on the run-up estimator. The physical tests of the Gijón breakwater were conducted with very high permeable core (90-tonne cube units), which highly affects wave overtopping, wave run-up and wave forces on crown walls. Martín et al. (1999) used the hypothesis of Saville (1962) to estimate wave forces generated by irregular waves.

Berenguer and Baonza (2006) conducted a set of 2D physical tests of mound breakwaters with crown wall using irregular waves in non-breaking conditions. Berenguer and Baonza (2006) proposed a method to estimate wave forces on crown walls without the assumption of pressure continuity. Their formulas calculate the horizontal force associated to an exceedance probability of 0.1% ($Fh_{0.1\%}$) and the associated maximum up-lift force ($Fv(Fh_{0.1\%})$), considering the damage level and the type of armor.

Molines (2016 and 2011) analyzed the 2D tests conducted by Smolka et al. (2009) of cube and Cubipod armored mound breakwaters with irregular waves in non-breaking conditions. Molines (2016 and 2011) did not assume pressure continuity between horizontal and up-lift pressures. The formulas given by Molines (2016 and 2011) estimate the horizontal force associated to an exceedance probability of 0.1% ($Fh_{0.1\%}$) and the associated maximum up-lift force ($Fv(Fh_{0.1\%})$). Molines (2016 and 2011) considers the effect of the type of armor through the roughness coefficient (γ_f) widely used in wave overtopping estimators (see EurOtop, 2018) and the influence of the foundation level on the wave forces on crown walls.

Finally, Molines et al. (2018) pointed out the relevance of wave overtopping to estimate wave forces on crown walls and provide estimators of wave forces based on the mean wave overtopping discharges.

Focusing on existing methods given in the literature to estimate wave forces on crown walls, there is a high hetereogeneity on the explanatory variables and the estimated forces. This study analyzes the crown wall stability using the physical tests described by Smolka et al. (2009) focusing on the questionable hypothesis of a pressure continuity between the horizontal pressure on the lower edge of the vertical wall and the up-lift pressure on the seaward edge of the crown wall base to estimate forces on the crown wall.

2 Experimental methodology

In this study, the 2D physical tests described by Smolka et al. (2009) are analyzed. Tests were conducted in the wave flume of the Laboratory of Ports and Coasts at the *Universitat Politècnica de València* (LPC-UPV). The tested cross sections (Figure 3) correspond to conventional double-layer cube and single- and double-layer Cubipod armored mound breakwaters with crown wall and without toe berm. 1000 irregular wave trains with JONSWAP spectrum (γ=3.3) were generated. Test series ranged 5.5< Hs(cm) <16.2; 0.9< Tp(s) <3.6; h(cm)= 50 and 55; 20.33< Rc(cm) <26.33; 11< Ac(cm) <24; Gc(cm)=12; 0.33< Fc(cm) <5.33; Ch(cm)=20 and 26; Cb(cm)=30, where Fc, Ch and Cb are the foundation level, the crown wall height and the length of the crown wall base, respectively.

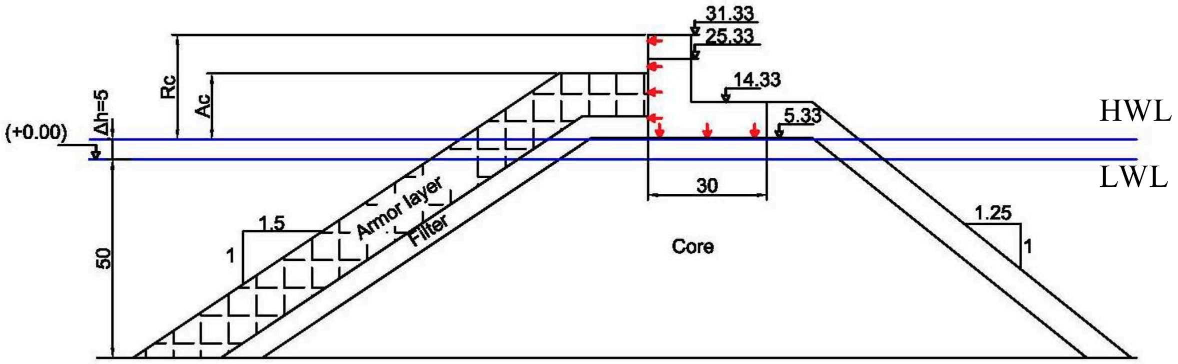

Fig. 3. Cross-section tested by Smolka et al. (2009). Pressure transducers in red. Dimensions in cm.

Wave characteristics, wave forces and wave overtopping were measured with 8 wave gauges, 7 pressure transducers and a chute with a weighting overtopping box, respectively. Incident and reflected waves were separated using the LASA-V method (Figueres and Medina, 2004), which can deal with non-stationary and non-linear Stokes V waves.

Pressure sensors placed in dry positions showed noise in some cases which was eliminated using moving average techniques, a common procedure in time series analysis (see Figure 4a). Wave forces exceeded by 0.1% of the waves were calculated using the filtered registers assuming that each point of the crown wall takes the pressure value of the nearest pressure sensor (see Figure 4b).

The model does not correspond to any specific prototype, but it could represent a typical Spanish Atlantic breakwater at a scale around 1/80. The core material was scaled following the Burcharth et al. (1999) recommendations in order to properly represent the turbulent flow inside the porous media.

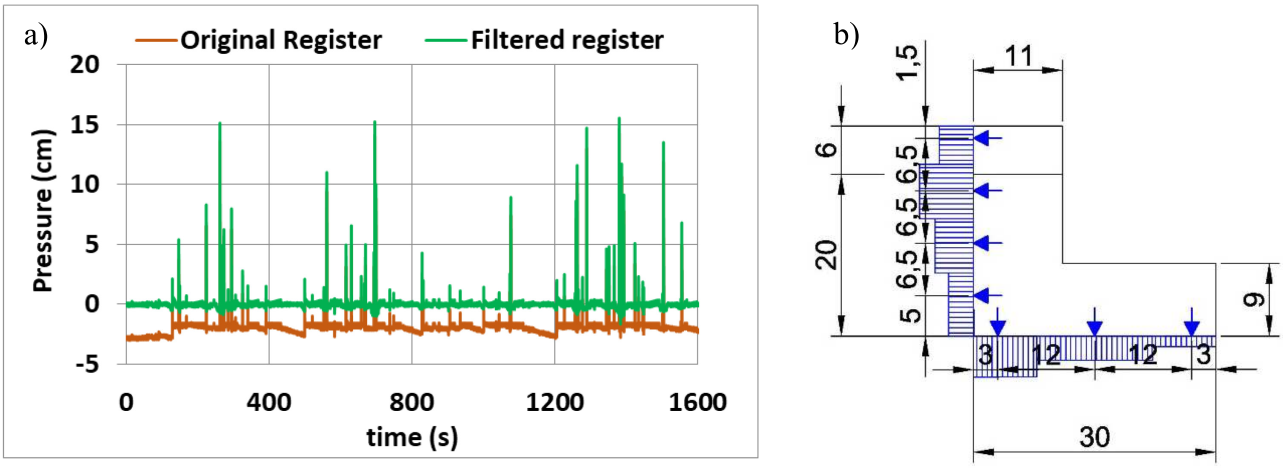

Fig. 4. a) Original and filtered register of a pressure transducer in a dry position. b) Rectangular pressure distribution around each pressure sensor. Dimensions in cm.

3 Analysis of results

In this study, the relative mean squared error given by Eq. (1) is used to measure the goodness of fit:

$$rMSE = \frac{MSE}{Var} = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{(o_i - e_i)^2}{Var(o_i)} \tag{1}$$

where MSE is the mean squared error, Var is the variance of the measurements, N is the number of data, o_i is the observed value and e_i is the estimated value. 0%≤ rMSE ≤100% estimates the proportion of variance not explained by the model; the lower the rMSE, the better the estimation.

Figure 5a shows the estimation of horizontal forces given by Pedersen (1996), Martín et al. (1999), Berenguer and Baonza (2006), Norgaard et al. (2013) and Molines (2016). Most of the existing formulas reasonably predict the horizontal forces with low dispersion. Figure 5b illustrates the estimation of the up-lift forces; these forces show a high dispersion of results depending on the estimator.

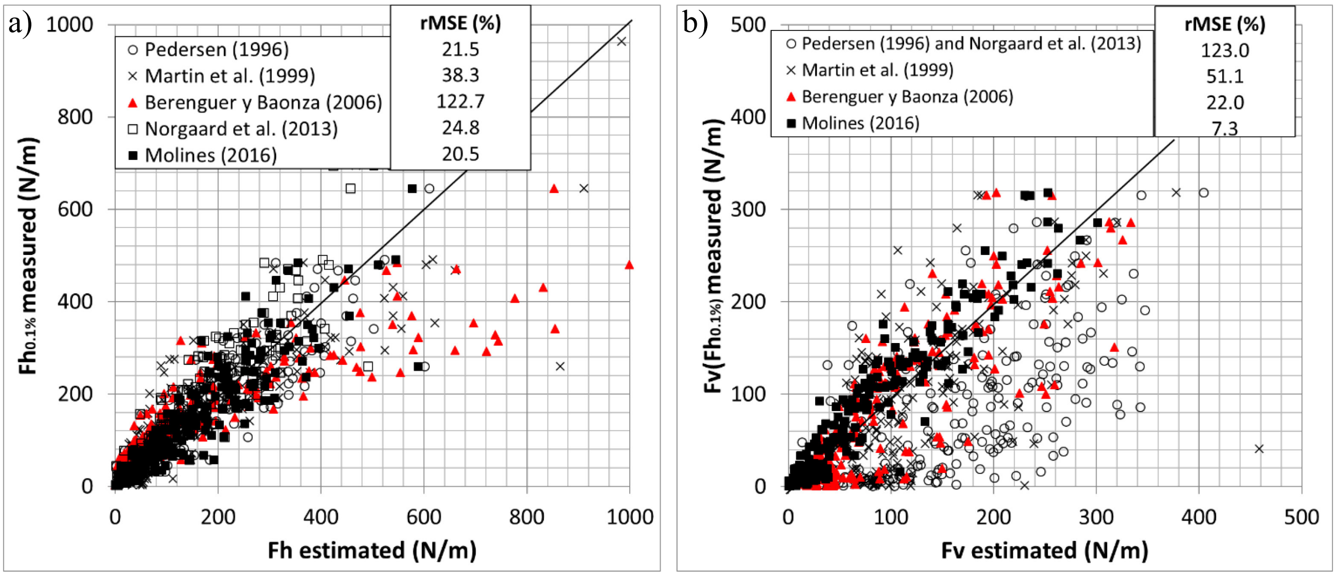

Fig. 5. Cross validation graph of a) horizontal forces and b) up-lift forces on crown walls.

3.1 *Wave forces on crown walls predicted by Molines (2016)*

Figure 6 illustrates the explanatory dimensionless variables used by Molines (2016) to estimate horizontal and up-lift wave forces:

- $\gamma_f R_u/R_c$ is the dimensionless run-up which relates the run-up level with the crown wall freeboard. It is related to the higher level of water that reaches the crown wall. A similar variable is used by Pedersen (1996) and Martín et al. (1999). The roughness factors derived by Smolka et al. (2009) are used to consider the influence of the type of armor. The estimaton of run-up, R_u, given by Van der Meer and Stam (1992) is used.
- $(R_c\text{-}A_c)/Ch$ represents the crown wall area which is not protected by the crest berm. It is accepted in the literature that the area protected by the crest berm receives lower forces than unprotected areas. When $R_c=A_c$, the crown wall is completely protected by the armor units in the crest berm.
- $(L_m/G_c)^{0.5}$ represents the relationship between the local wavelength (using T_{01}) and the crest berm width, similar to a variable used by Pedersen (1996). Wider crest berms will lead to lower forces on the crown wall because more energy is dissipated before reaching the crown wall.
- F_c/Ch represents the foundation level of the crown wall, which is similar to a variable used by Berenguer and Baonza (2006). Higher foundation levels will reduce forces on crown walls

The forces were made dimensionless as follows:

- $Fh_{0.1\%}/(0.5\rho g Ch^2)$, dimensionless horizontal force.
- $Fv(Fh_{0.1\%})/(0.5\rho g ChCb)$, dimensionless up-lift force.

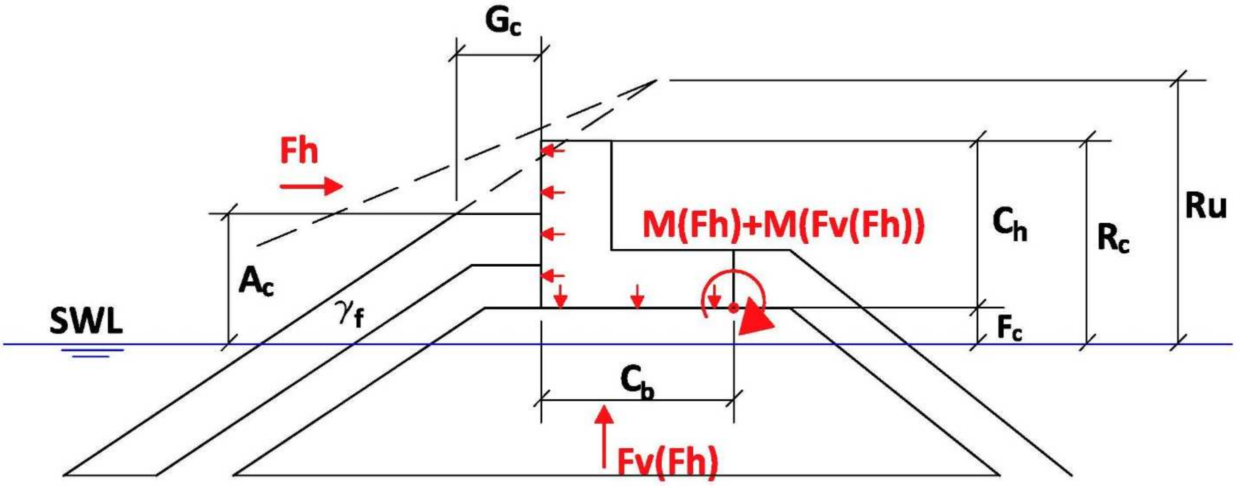

Fig. 6. Explanatory variables to estimate wave forces. Forces, moments and pressure sensors in red.

3.2 *Influence of the armor layer on the wave forces on crown walls*

Figure 7 illustrates the dimensionless run-up in the horizontal axis and the horizontal wave forces in the vertical axis. Tests have been grouped depending on the degree of protection offered by the armor layer: Figure 7a illustrates double-layer randomly-placed cube armors and single-layer Cubipod armors with $0.26<(R_c\text{-}A_c)/Ch<0.28$ while Figure 7b illustrates double- and single-layer Cubipod armors with $0.44<(R_c\text{-}A_c)/Ch<0.47$.

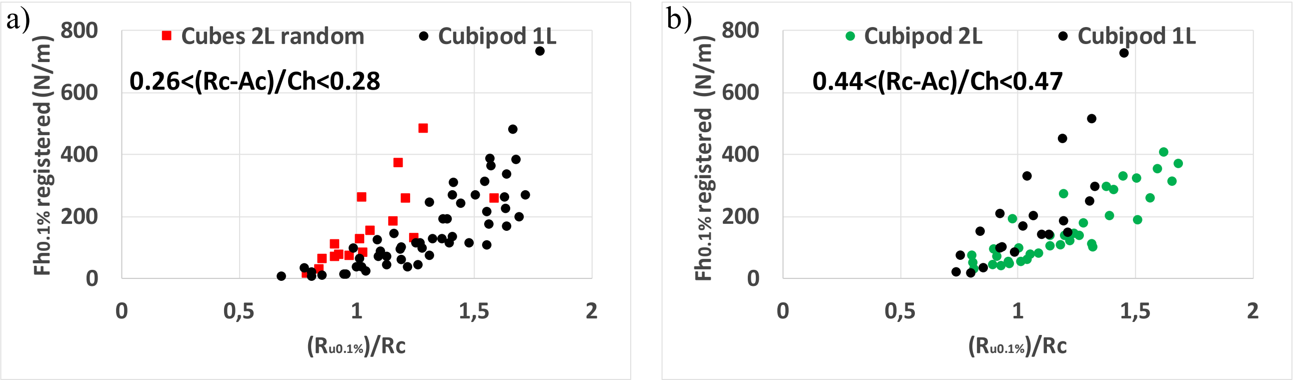

Fig. 7. Influence of wave run-up and type of armor on wave forces on crown walls.

Figure 7a shows that crown walls built on top of double-layer cube armored mound breakwaters have higher wave forces than those constructed on top of single-layer Cubipod armored mound breakwaters with the same design storm and structural characteristics. Figure 7b shows that crown walls built on top of 1L Cubipod armored mound breakwaters have higher forces than those constructed on top of 2L Cubipod armored mound breakwaters. The same trend is represented by the roughness factor used in overtopping estimators: γ_f=0.50 (2L cubes, randomly-placed)> γ_f=0.46 (1L Cubipods)> γ_f=0.44 (2L Cubipods). Therefore, the γ_f can be used to consider the influence of the armor layer on the wave forces on crown walls.

3.3 *Influence of the foundation level on wave forces on crown walls*

The vertical axis in Figure 8 represents the registered maximum up-lift force generated by the wave that caused the horizontal force exceeded by 0.1% of the waves. The horizontal axis in Figure 8 represents the up-lift force assuming a triangular distribution calculated with the horizontal pressure on the lower edge of the vertical wall produced by the horizontal force exceeded by 0.1% of waves.

Square symbols represent tests with foundation level around zero, where both forces provide similar results and therefore the continuity of pressures may be acceptable (Pérez et al., 2010 and Clavero et al., 2012). However, in tests with high foundation levels (triangle symbols), the assumption of the pressure continuity provides up-lift forces approximately three times higher than the registered up-lift force. Therefore, the foundation level must be explicitly included as an explanatory variable to estimate up-lift forces on crown walls.

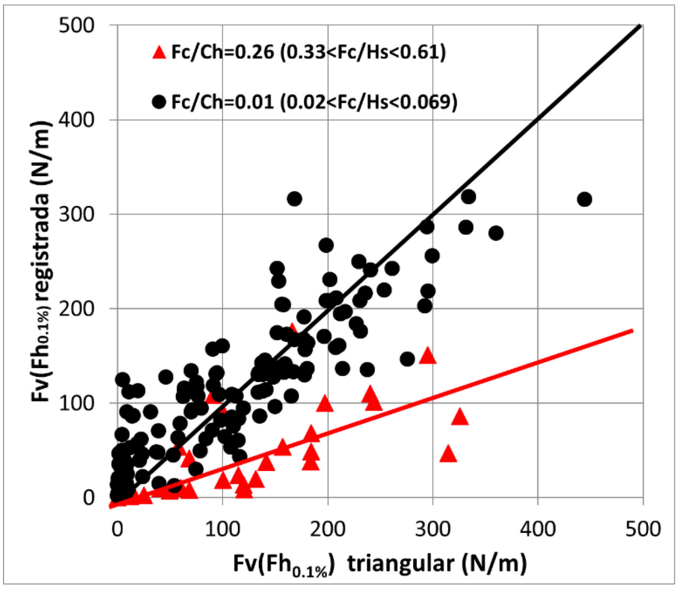

Fig. 8. Comparison between registered up-lift force and estimated up-lift force assuming pressure continuity.

4 Conclusions

The present study analyzes the 2D physical tests conducted by Smolka et al. (2009). Double-layer cube and Cubipod armored breakwaters and single-layer Cubipod armored breakwaters with crown walls were tested. The type of armor affects the wave forces on crown walls and its effect can be considered with the roughness factor (γ_f) widely used in wave overtopping estimators. Molines et al. (2018) noted that dimensionless wave forces on crown walls are higher with higher dimensionless mean overtopping discharges. As γ_f=0.50 (2L cubes, randomly-placed)> γ_f=0.46 (1L Cubipods)> γ_f=0.44 (2L Cubipods), wave forces on crown walls of cube armored mound breakwaters are higher than those on 1L Cubipod armored mound breakwaters and both are higher than those on 2L Cubipod armored mound breakwaters.

This study illustrates that considering the pressure continuity between the horizontal pressure in the lower edge of the vertical wall and the up-lift pressure in the seaward edge of the crown wall base together with a high foundation level may overestimate up-lift forces with a factor of 3. Conventional mound breakwaters are usually constructed with a foundation level above mean sea water level; therefore, the foundation level must be explicitly considered to estimate up-lift wave forces. The higher the foundation level, the lower the up-lift forces.

5 Acknowledgements

The authors acknowledge the financial support of FEDER, Spanish *Ministerio de Ciencia, Innovación y Universidades* (Grant RTI2018-101073-B-100), *SATO (Grupo OHL)*, *Universitat Politècnica de València (*Grant SP20180111*, Primeros Proyectos de Investigación (PAID-06-18),Vicerrectorado de Investigación, Innovación y Transferencia de la Universitat Politècnica de València)* and *Generalitat Valenciana* (Grant AEST/2019/004).

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